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(54) Optical phase retarder

(57) An optical phase-retarder device comprises first and second light-transmissive plates 1 and 2 with an electro-optic medium 7 therebetween, and first and second electrode structures 3 and 4 on the first and second plates 1 and 2 respectively, for applying an electric field to the electro-optic medium, the first electrode structure 1 comprising an electrode the resistance of which varies along its length, due to variations in the width of the electrode, to compensate for non-linearity in the phase-retardation/applied voltage characteristic of the electro-optic material. The electro-optic medium is preferably a liquid crystal.

Fig. 1.

(b)

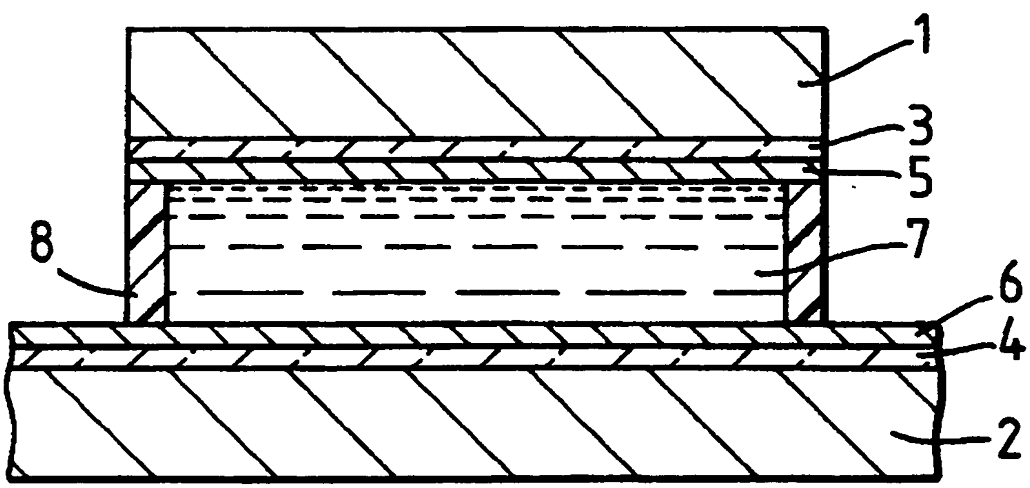

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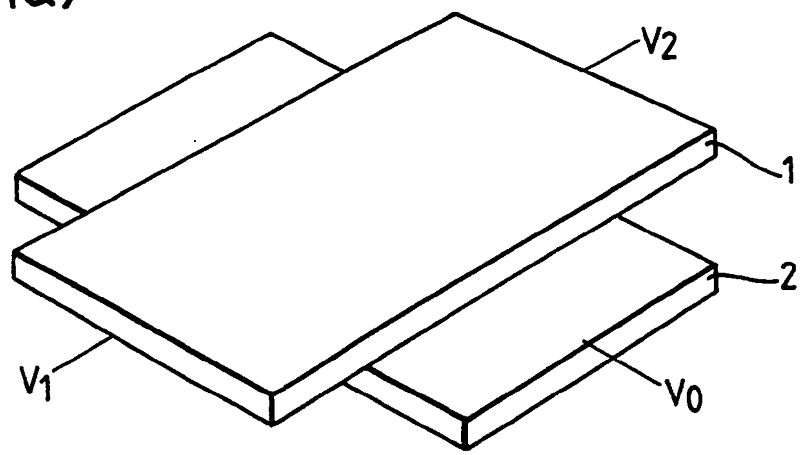
Fig.1.

(a)



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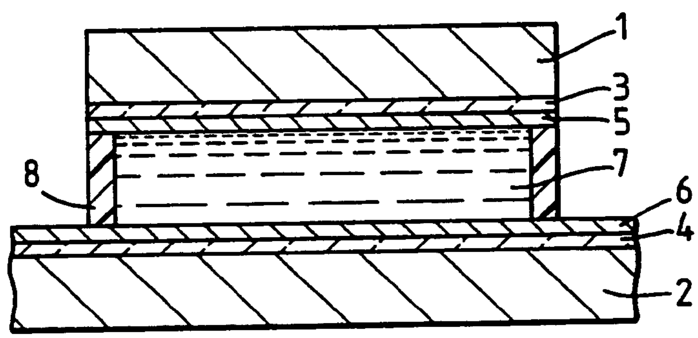


Fig. 2.

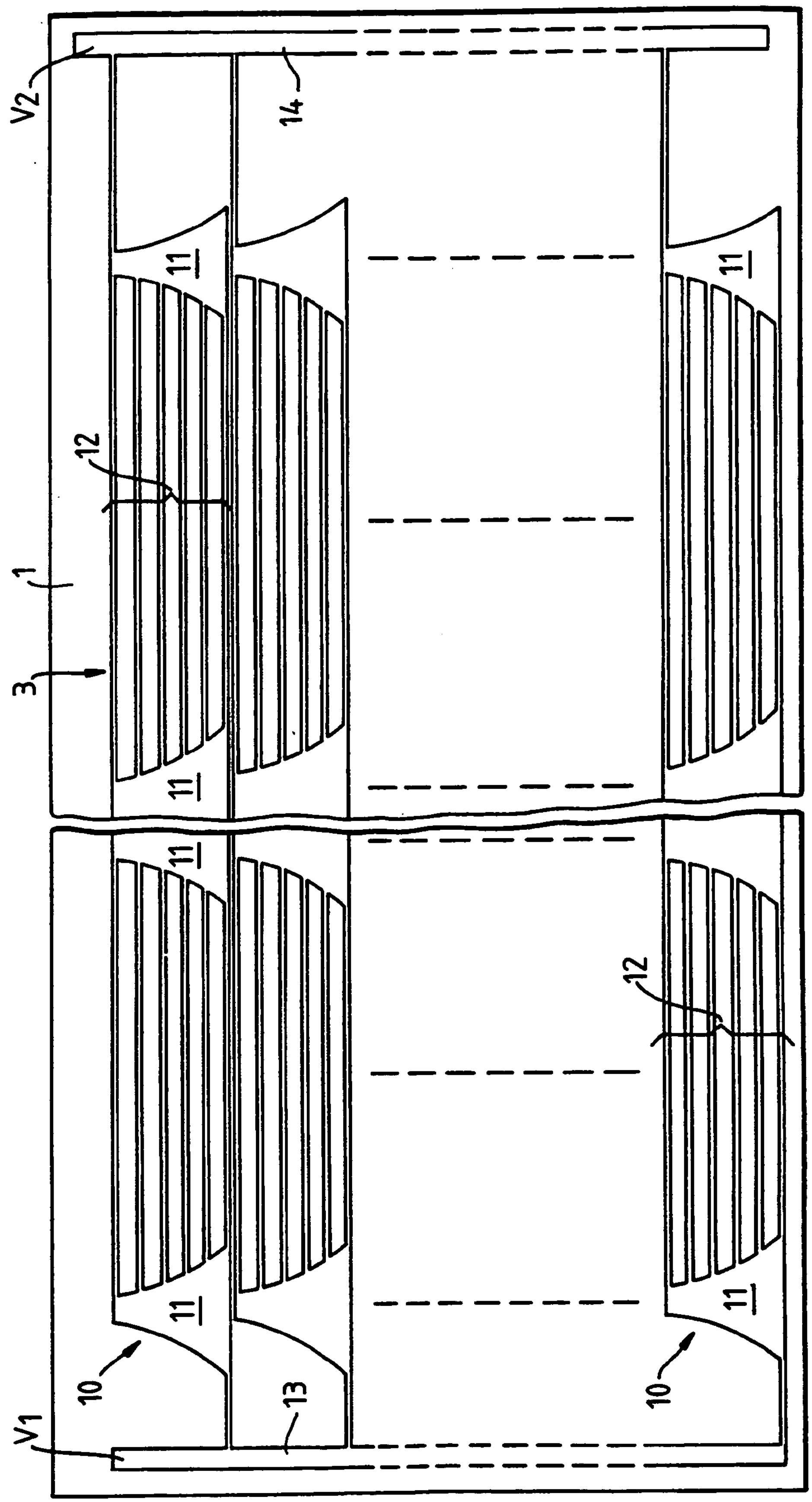


Fig. 3.

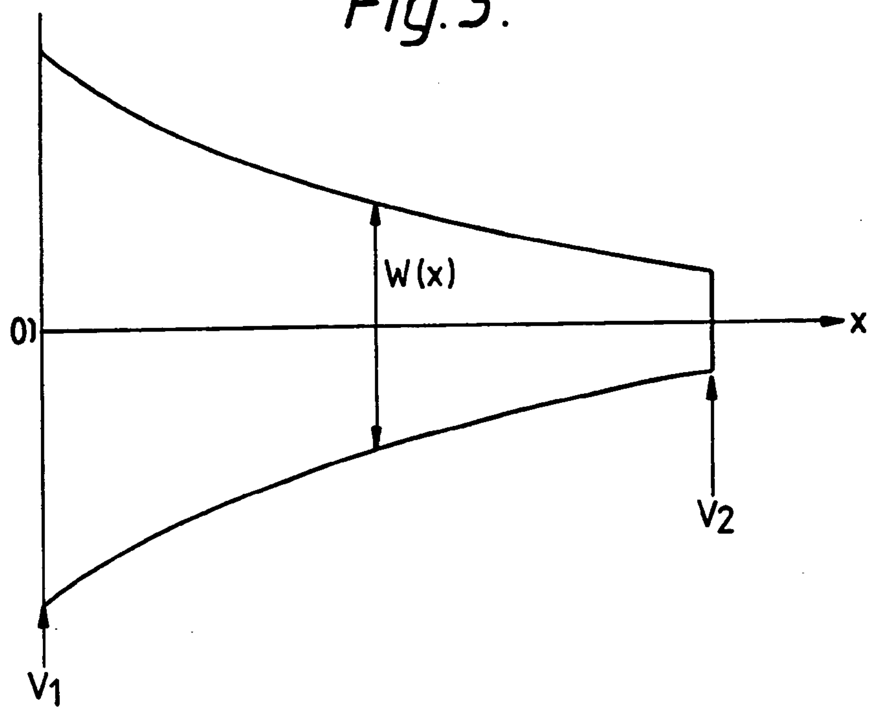


Fig. 4.

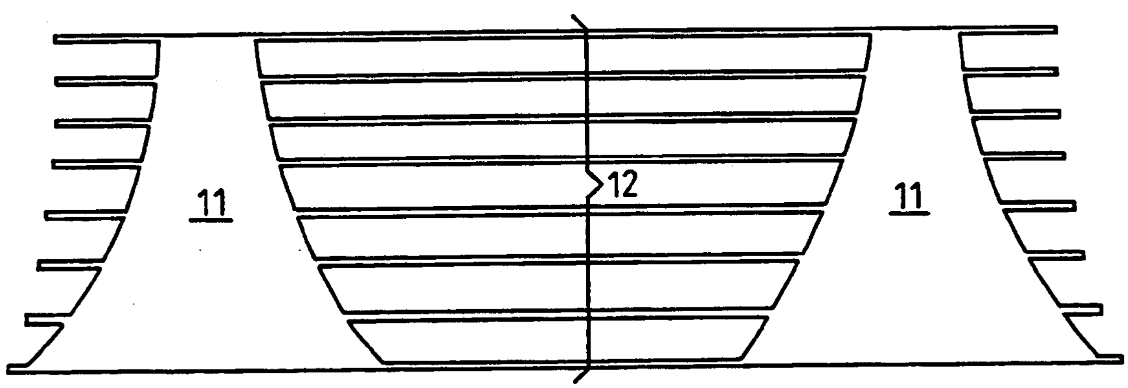
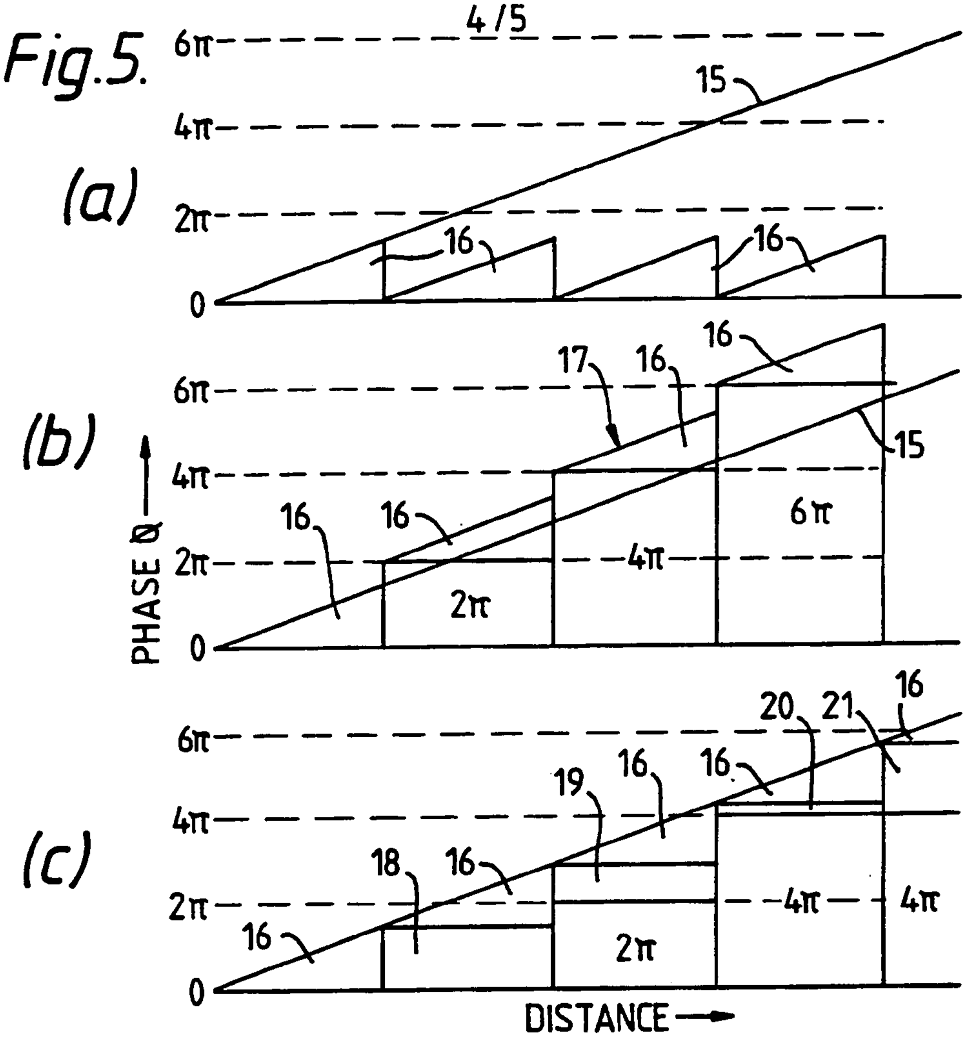


Fig.5.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(b)
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PHASE Ø
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Fig.6.

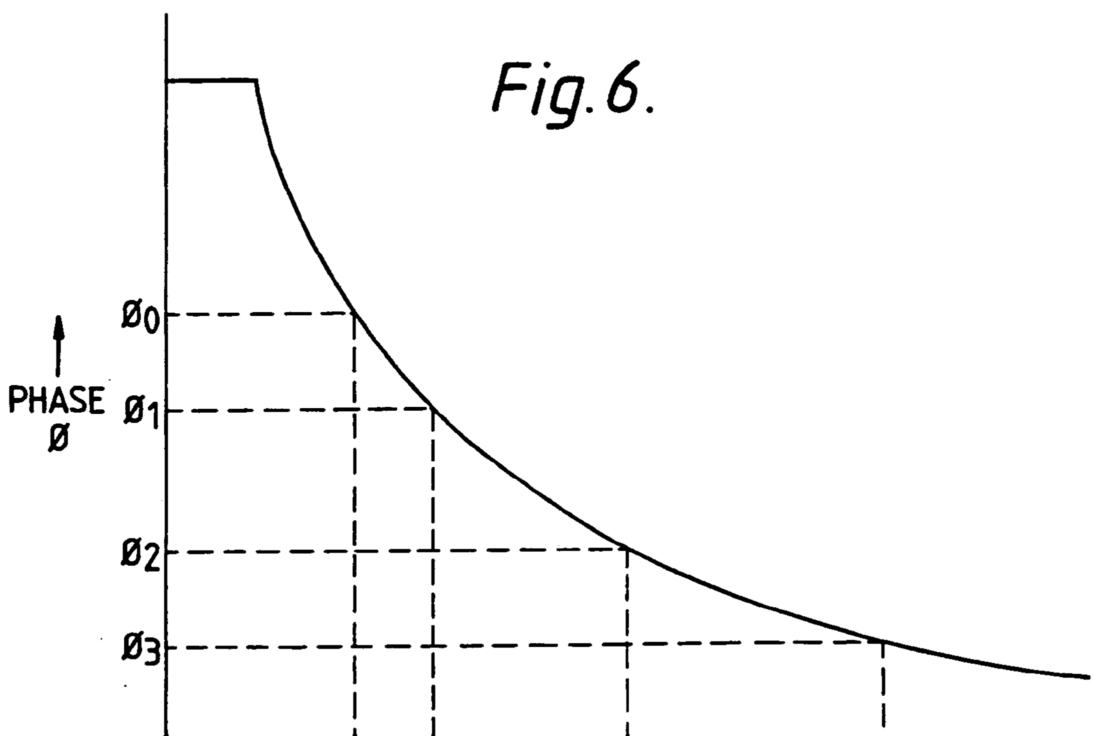
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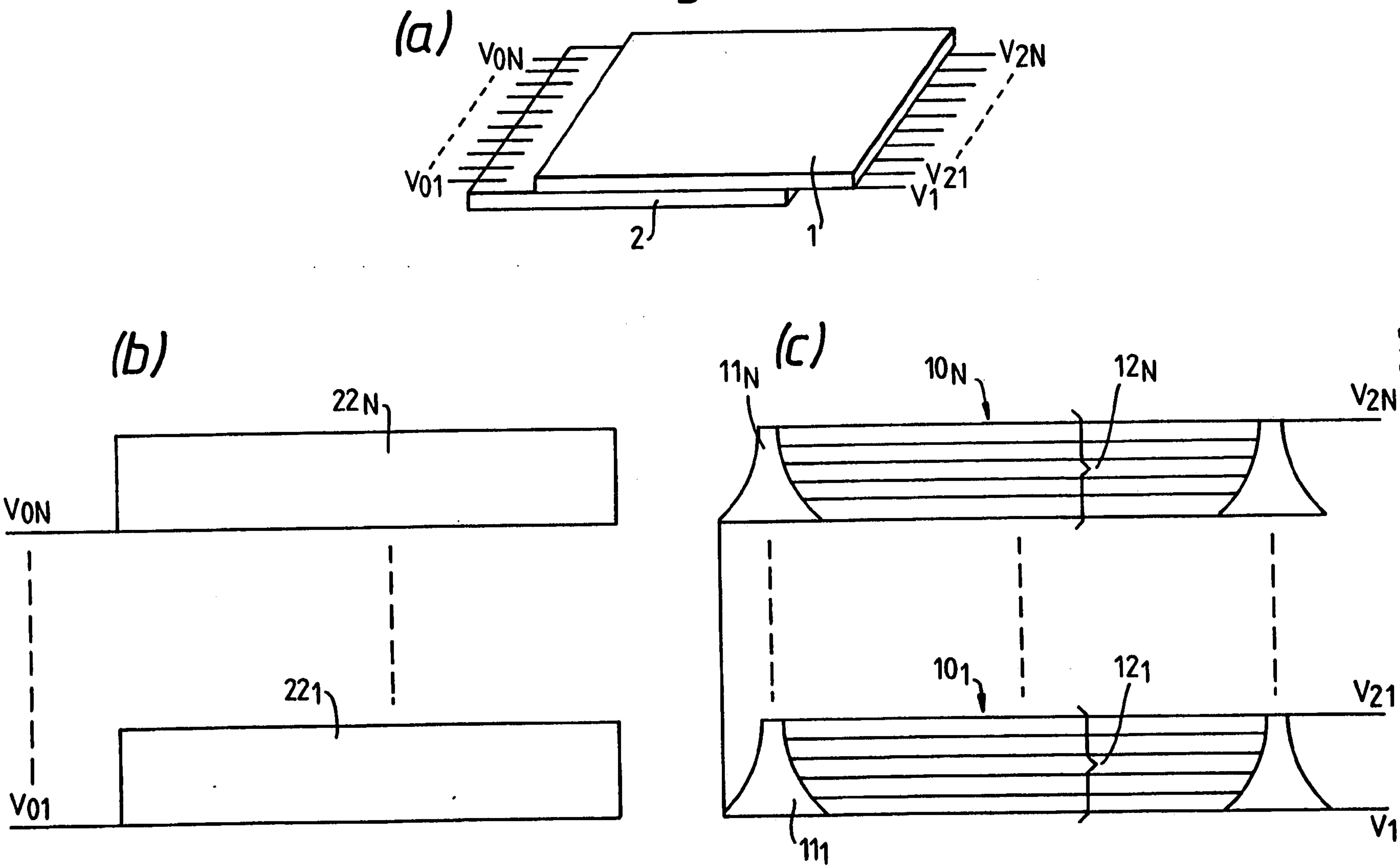
Fig. 7.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Optical Devices

This invention relates to optical devices, and particularly to variable optical phase-retarder devices.

In our European Patent Specification No.0258996, electrically-switchable optical components are described which exploit the principle of Fresnel zones. In one example, a zone plate structure is described. When not activated, this structure acts as a uniform component, but when a suitable voltage is applied to electrodes of the zone plate, each alternate zone introduces a phase shift of π radians in the light passing through the structure. The component then becomes a Fresnel phase zone plate and is a focusing device. Hence, a lens-like component can be constructed, the focal length of which can be switched from infinity (i.e. acting as a uniform component) to some finite value.

Such a lens, being a binary structure, has a limited optical efficiency, i.e. only a small proportion of the incident light is directed to the focus. For the binary phase retarder lens described above, a maximum of 41% of the incident light in the correct polarisation appears at the principal focus. It is well known that to improve the efficiency a larger number of phase levels must be used, as shown in the above-mentioned patent specification. In principle, this can be achieved by a fine subdivision of each Fresnel zone and providing each electrode thus created with its own

voltage.

We have shown in our published British Patent Specification No. 2269042A that, using a bus-bar interconnect scheme, four-level devices can be realised, the electrode pitch of which is determined solely by the practical ability to define the electrode structure, typically < 5μm. Devices with more than four phase levels per zone require that each electrode be independently connected to an external voltage source. This can be achieved at present only with a pitch of about 100μm. Accordingly, optically-efficient devices are constrained to have very low optical power (because of the enforced large zone spacing), or massive fan-out of the electrodes must be implemented.

In a second embodiment described in our above-mentioned European patent specification, a saw-tooth pattern of phase retardation causes the device to act as a switchable prism or beam deflector. Again, a binary device is inefficient. Such a device deflects only 41% of the incident (polarised) light in the desired direction (i.e. the first order deflection). Another 41% is deflected by an equal angle in the opposite sense. The remaining light is distributed among higher orders of diffraction, since the device acts as a phase diffraction grating. To improve its efficiency, more phase levels per zone (or grating period) are necessary. Above four levels, interconnection is the limiting factor, as was described above.

Also in that European specification, an alternative method is described for setting up the required variations in voltage by using electrode structures with spatially-varying resistivity. It is suggested therein that the thickness of the electrode could be varied or high resistance electrodes with highly-conductive strips deposited along two edges could be used, in either case with a different voltage applied to the two edges of the underlying electrode. There are several disadvantages to these proposals. Firstly, constructing an electrode (typically of indium tin oxide (ITO) of thickness 30nm) the thickness of which varies in a controlled fashion is extremely different and such electrode is not

suited to mass-production. Secondly, for a typical Fresnel zone electrode of width, say, 50μm and length, say 1cm, to sustain a voltage difference of, say, 1V, across its width without drawing an extremely large current, would require the underlying electrode to have a very large sheet resistance (in excess of $1 \times 10^5 \Omega$/square to achieve a current <1mA with these parameters). It is at present extremely difficult to achieve sheet resistances $>10^3 \Omega$/square in continuous films and, moreover, the electro-optic material (typically liquid crystal) forming the device, and the substrate upon which the electrode is deposited, provide leakage paths with resistances which may be comparable to that of the electrode. Thirdly, it is well known that the retardation versus voltage relation of electro-optic materials, and of liquid crystals in particular, is non-linear. Therefore, a linear distribution of voltage along the electrode is not satisfactory.

The above-mentioned devices all operate with either zero voltage or a voltage of a predetermined value applied to the electrode structure such that the designed optical effect is either present or not. Thus, in the case of the lens, the light is either brought to a particular focus or the lens is inactive. The focal length is predetermined by the design of the device. Similarly, for the beam deflecting device, the deflection angle is either zero or some predetermined value. To achieve continuously variable optical effects (e.g. variable focal length or variable deflection angle), it is suggested in EP 0258996 that finer, uniformly-spaced electrodes could be used, of which selected ones would be activated to provide the required Fresnel zone pattern. Again, this proposal has the disadvantage that each of the above-mentioned fine electrodes must be individually addressable.

It is an object of the present invention to provide an improved optical phase retarder device.

According to the present invention, there is provided an optical phase retarder device, comprising first and second light-transmissive plates with an electro-optic medium therebetween; first and second electrode structures on said first and second

plates, respectively, for applying an electric field to the electro-optic medium; said first electrode structure comprising an electrode the resistance of which varies along its length, due to variations in the width of the electrode, to compensate for non-linearity in the phase-retardation/applied voltage characteristic of the electro-optic material.

Distribution electrode means may be coupled to the varying-width electrode to pick off the voltage distribution occurring on said electrode and to distribute it in the plane of the varying-width electrode in a direction perpendicular to the length of said electrode.

Embodiments of the invention will now be described, by way of example, with reference to the accompanying drawings, in which

Figures 1(a) and 1(b) are, respectively, schematic pictorial and cross-sectional views of a liquid crystal cell,

Figure 2 is a schematic plan view of part of an electrode structure of a liquid crystal phase retarder device in accordance with the invention,

Figure 3 is a schematic plan view of a tapered electrode element of the device,

Figure 4 is an enlarged schematic plan view of part of the electrode structure of Figure 2,

Figure 5(a), 5(b) and 5(c) illustrate, respectively, different phase profiles which can be generated by the electrode structure,

Figure 6 is a graph of phase versus voltage for a liquid crystal display element, and

Figures 7(a), 7(b) and 7(c) are a pictorial view, an underneath plan view and a top plan view, respectively, of an alternative configuration of device in accordance with the invention.

Referring to Figure 1 of the drawings, a conventional liquid crystal cell comprises two substantially parallel transparent (e.g. glass) plates 1 and 2. The plate 1 carries, on its lower surface, a patterned electrode layer 3 formed of transparent conductive material, such as indium tin oxide (ITO). The plate 2

carries, on its upper surface, a uniform, unpatterned layer 4 of such transparent conductive material. On the lower surface of the layer 3 and the upper surface of the layer 4 are alignment layers 5 and 6, respectively. A layer 7 of liquid crystal material is contained between the layers 5 and 6 and is retained by a seal 8. The thickness of the space containing the layer 7 is defined by spacers (not shown). The alignment layers 5 and 6 are provided to align the liquid crystal material into a uniform, untwisted, planar configuration. Connections to voltage sources V_1 and V_2 are made to the electrode pattern 3 on the plate 1, and a voltage V_0 is connected to the electrode 4 on the plate 2 from an external source.

Figure 2 illustrates, in plan view, a configuration of the electrode structure 3 for a beam deflector or prism. The structure comprises patterned sections 10, which are replicated many times over the area of the plate 1. Each section 10 comprises a tapered conductive area 11, which is connected to the adjacent area 11 by a set of parallel narrow conductive lines 12 which are spaced apart along the length of the area 11. The wide end of each tapered area 11 is connected to a busbar 13 to which the voltage V_1 is applied. The narrow end of each area 11 is connected to a busbar 14 to which the voltage V_2 is applied.

The properties of the patterned sections will now be described with reference to Figure 3. Let the axis Ox lie along the length of the taper, the width of which at a distance x from the origin is W(x). If the electrode has a sheet resistance σ ohms/square, then the resistance at a distance x along the taper is given by

$$R(x) = \sigma \int_0^x \frac{dx}{W(x)} \qquad (1)$$

and the current flowing due to a potential difference (V_2-V_1) connected across the taper is

$$I = \frac{(V_2-V_1)}{\sigma}\left[\int_0^d \frac{dx}{W(x)}\right]^{-1} \qquad (2)$$

where d is the total length of the taper, so that the voltage distribution V(x) is given by

$$V(x) = IR(x) = I\sigma\int_0^x \frac{dx}{W(x)}$$

$$= (V_2-V_1)\int_0^x \frac{dx}{W(x)}\left[\int_0^d \frac{dx}{W(x)}\right]^{-1} \qquad (3)$$

If W(x) is constant, then

$$V(x) = (V_2-V_1)x/d \qquad (4)$$

is linear in x.

However, the normalised retardation, $\phi(V)$, that is the ratio of the retardation $\delta(V)$ of an untwisted liquid crystal layer experiencing an applied voltage V to the retardation $\delta(0)$ of the same layer with no applied voltage, may be written as

$$\phi(V) = \delta(V)/\delta(0) = \begin{cases} 1 & V < V_A \\ 1 - C\,[V-V_A]^2 & V_A < V < V_B \\ A/(V-B) & V > V_B \end{cases} \qquad (5)$$

where $\delta(V)$ is the phase retardation at a voltage V, and A,B and C are empirical constants. For a typical liquid crystal material the voltages V_A and V_B are about 0.7V and 1.5V, respectively. It will be apparent that the relationship between the normalised retardation and voltage is non-linear, so that a linear voltage distribution (equation (4)) does not provide the required linear distribution of retardation.

In the present invention the width W(x) of the electrode

is selected such that, despite the effect of any non-linearity in $\phi(V)$, the phase profile has the required form. For example, let the desired phase profile be $\phi(x)$, and let the inverse of the normalised retardation versus voltage relationship be defined as

$$f^{-1}(\phi) = V \tag{6}$$

Using, for example, equation (5) to define $\phi(V)$,

$$f^{-1}(\phi) = V = \begin{cases} [(1-\phi)/C]^{\frac{1}{2}} + V_A & V_A < V < V_B \\ A/\phi + B & V > V_B \end{cases} \tag{7}$$

Then, from equations (3) and (6) it can be shown that the variation of width $W(x)$ required to achieve the phase variation $\phi(x)$ is given by

$$W(x) = I\sigma\left[\frac{d}{dx}\,[f^{-1}\,(\phi(x))]\right]^{-1} \tag{8}$$

Again using the example of equation (5) in the region $V > V_B$, if a linear profile

$$\phi(x) = \phi_0 - Kx \tag{9}$$

is required, then

$$W(x) = I\sigma(\phi_0 = Kx)^2/AK \tag{10}$$

i.e. $W(x)$ is a taper quadratic in x.

It will be apparent that, given the normalised retardation versus voltage relation $\phi(V)$, a taper $W(x)$ can be designed to provide any desired phase profile $\phi(x)$ necessary to achieve the

desired Fresnel zone phase front.

There are limits on the maximum and minimum width values W(x). The minimum value is set by the ability to define the small structures accurately. The maximum value is set by the permissible level of current load. In practice, the smallest and largest widths may be, for example, 5μm and 50μm, respectively. For a useful optical device, however, it is undesirable for the active cell area to be limited to such small dimensions.

This problem is alleviated in the embodiments of Figures 2 and 4 by provision of the narrow conductors 12 which interconnect the adjacent areas 11. Due to the resistivity and shape of each area 11, there will be a non-linear potential gradient along the length of the area. The conductors 12 are connected to respective points along the length of the area 11, so the conductors adopt the same potentials as those points. The conductors 12 therefore distribute the voltage profile V(x) produced by the area 11 over a much wider area than the area 11. As the distribution conductors 12 lie on equipotential lines, no current flows through them, so their resistivity may have any desired value. The influence of the distribution electrodes extends into the gap between them only by a distance approximately equal to the thickness of the electro-optic layer. Hence, in the case of a nematic liquid crystal device having a typical cell spacing of 5-20μm, the separation of the distribution electrodes must also be 5-20μm.

The electrode structure shown in Figure 4 comprises one Fresnel zone in an optical device. As depicted, this would be one zone of a Fresnel prism, providing a single triangular element of a sawtooth phase profile. To obtain an effective device, this structure is replicated as shown in Figure 2. Such an electrode structure thus provides the required phase profile over the entire active area of the device so that it functions with maximum optical efficiency, because V_1 and V_2 can be chosen so that the extent of the phase profile is $0-2\pi$ in each electrode region.

The embodiments so far described operate at fixed deflection angle or focal length, i.e. these devices can only be

switched on or off. In a further embodiment of the invention, an optical device can be tuned continuously rather than switched. Referring first to a single taper, as shown in Figure 3 or Figure 4, and equation (10), it is clear in this example that it is possible to change the value of K while maintaining W(x) fixed by suitable changes in ϕ_0 and I, i.e. the phase pedestal and the current flow through (or equivalently the voltage difference across) the taper. Hence the angle of a linear profile (equation (9)) can be continuously varied, thus providing the basic element of a continuously tunable device.

However, this is insufficient to achieve optically efficient tuning in the device as a whole. This will be apparent from Figure 5, in which is shown a desired phase front 15 along with individual sawtooth phase elements 16 which are generated by the zone structure in Figure 4. These elements 16 do not extend from 0-2π. Accordingly, if they are assembled into a single phase front, as shown in Figure 5(b), the resultant is given by a stepped line 17 which is constructed by adding multiples of 2π to the elements 16. However, the desired phase front 15 can be obtained, as shown in Figure 5(c), by adding the elements 16 to phase plateaux 18,19,20,21, the heights of which are different for each electrode section . The method of generating the elements 16 and the plateaux 18-21 is shown in Figure 6. Here, the phase difference $\Delta\phi$, which is the height of the elements 16, can be generated by many different voltage combinations. For example, the voltages V_0 and V_1, applied to a tapered electrode 11 would generate phases ϕ_0 and ϕ_1, respectively, which differ by $\Delta\phi$. The voltages V_2 and V_3 similarly generate phases ϕ_2 and ϕ_3, which also differ by $\Delta\phi$, but have different absolute values. Hence, the phase plateaux 18-21 can be obtained, together with the sawtooth elements 16, by suitable choice of the voltages on the tapered electrodes. In a practical device, there are three potential levels, shown as V_0, V_1 and V_2 in Figure 1, producing two potential differences applied to the cell. It is advantageous to keep constant one of the voltages applied to the tapered electrode so that the density of electrode connections is

minimised, and to vary one voltage on the taper and the voltage on the counter-electrode.

The device is constructed as shown in Figure 7 in which Figure 7(a) shows an overall pictorial view and the two electrode patterns as shown in Figure 7(b) and Figure 7(c). Counter electrodes 22_1---22_N are provided on the plate 2, each corresponding in area to, and aligned with, the electrode structures 10_1--- 10_N on the plate 1. Voltages V_{o1}---V_{oN} are applied to the counter electrodes 22_1---22_N, respectively. A voltage V_1 is applied to the wide edge of each tapered electrode 11_1,---11_N, and voltages V_{21}---V_{2N} are applied to the narrow edges. This construction provides a device which is both optically efficient and continuously tunable.

The above embodiments relate to a device configured as a tunable prism. It will be apparent that the same principles can be applied to the design of a continuously-variable Fresnel lens, either cylindrical or spherical.

Other liquid crystal configurations, such a homeotropically aligned fluid with negative dielectric anisotropy, could alternatively be used. Moreover, other electro-optic materials besides liquid crystal materials may also be effective in such devices.

To summarise, the invention provides thin film optical devices based on the Fresnel zone principle which are both optically efficient because the desired phase front is correctly generated by the design, and continuously tunable by virtue of the design, without having to connect to and control very fine electrodes.

Claims

1. An optical phase-retarder device, comprising first and second light-transmissive plates with an electro-optic medium therebetween; and first and second electrode structures on said first and second plates, respectively, for applying an electric field to the electro-optic medium; said first electrode structure comprising an electrode the resistance of which varies along its length, due to variations in the width of the electrode, to compensate for non-linearity in the phase-retardation/applied voltage characteristic of the electro-optic material.

2. A device as claimed in Claim 1,comprising distribution electrode means coupled to the varying-width electrode to pick off the voltage distribution occurring on said electrode and to distribute it in the plane of the varying-width electrode in a direction perpendicular to the length of said electrode.

3. A device as claimed in Claim 2, wherein the distribution electrode means comprises a set of spaced-apart substantially parallel electrically-conductive strips, each connected at one of its ends to a respective point on the length of the varying-width electrode.

4. A device as claimed in any preceding claim, comprising a plurality of said first electrode structures for defining a plurality of Fresnel zones.

5. A device as claimed in any preceding claim, comprising means to connect the ends of the or each varying-width electrode across a voltage source.

6. A device as claimed in Claim 4, comprising means to connect one end of the varying-width electrodes in common to a predetermined potential; and means to connect the other end of the varying-width electrodes each to a respective potential.

7. A device as claimed in any preceding claim, wherein the second electrode structure comprises a continuous layer of electrically-conductive material on said second plate.

8. A device as claimed in Claim 6, wherein the second electrode structure comprises a plurality of separate electrodes each substantially aligned with a respective one of the first electrode structures.

9. A device as claimed in any preceding claim, wherein the electro-optic medium is a liquid crystal material.

10. A device as claimed in Claim 9, wherein the electro-optic medium is a a nematic liquid crystal material.

11. A device as claimed in Claim 9, wherein the electro-optic medium is a homeotropically aligned fluid with negative dielectric anisotropy.

12. An optical phase-retarder device substantially as hereinbefore described with reference to the accompanying drawings.

Patents Act 1977 **Examiner's report to the Comptroller under Section 17** **(The Search report)**	Application number GB 9404619.0
Relevant Technical Fields (i) UK Cl (Ed.M) G2F (FAM, FCD, FCE, FSX) (ii) Int Cl (Ed.5) G02F 1/343	Search Examiner G M PITCHMAN Date of completion of Search 8 JUNE 1994
Databases (see below) (i) UK Patent Office collections of GB, EP, WO and US patent specifications. (ii) ONLINE DATABASES: WPI, CLAIMS	Documents considered relevant following a search in respect of Claims :- 1 to 12

Categories of documents

X: Document indicating lack of novelty or of inventive step.

Y: Document indicating lack of inventive step if combined with one or more other documents of the same category.

A: Document indicating technological background and/or state of the art.

P: Document published on or after the declared priority date but before the filing date of the present application.

E: Patent document published on or after, but with priority date earlier than, the filing date of the present application.

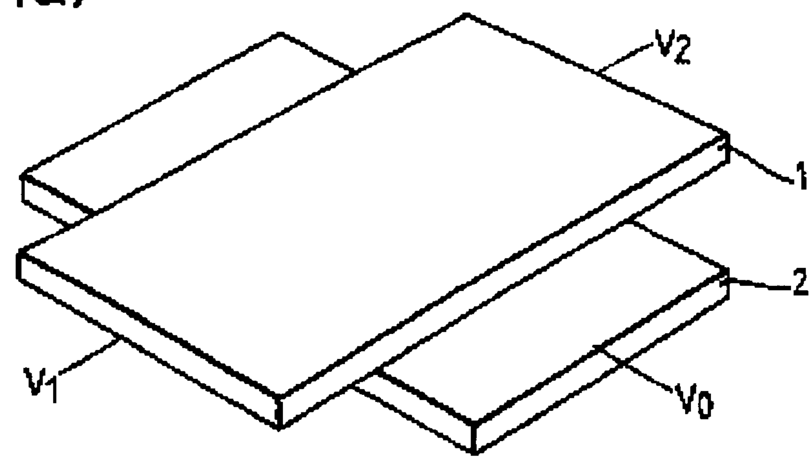
&: Member of the same patent family; corresponding document.

Category	Identity of document and relevant passages	Relevant to claim(s)
P,A	GB 2266599 A (SAMSUNG) see page 6 lines 9 to 19	1

Databases: The UK Patent Office database comprises classified collections of GB, EP, WO and US patent specifications as outlined periodically in the Official Journal (Patents). The on-line databases considered for search are also listed periodically in the Official Journal (Patents).

Fig.1.

(a)



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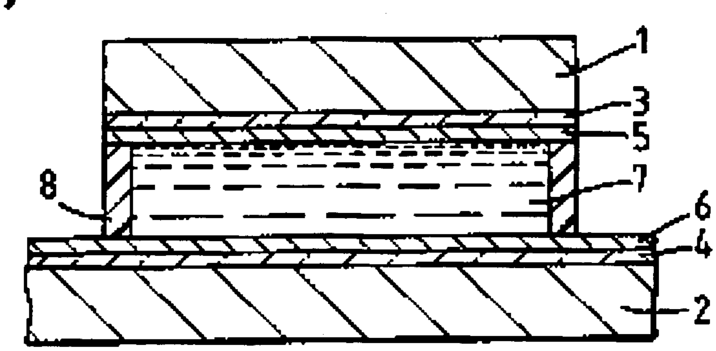


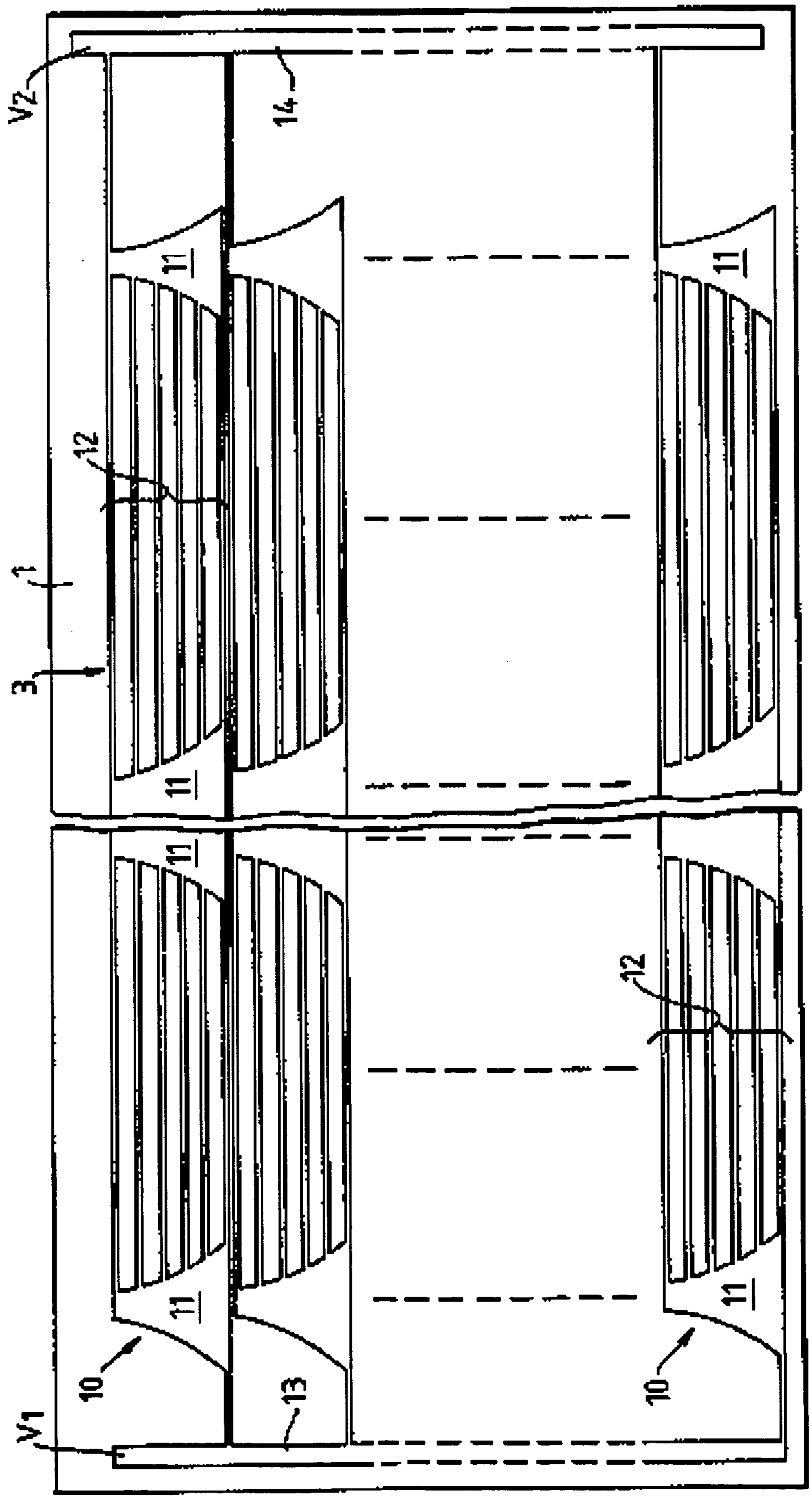


Fig. 2.

Fig. 3.

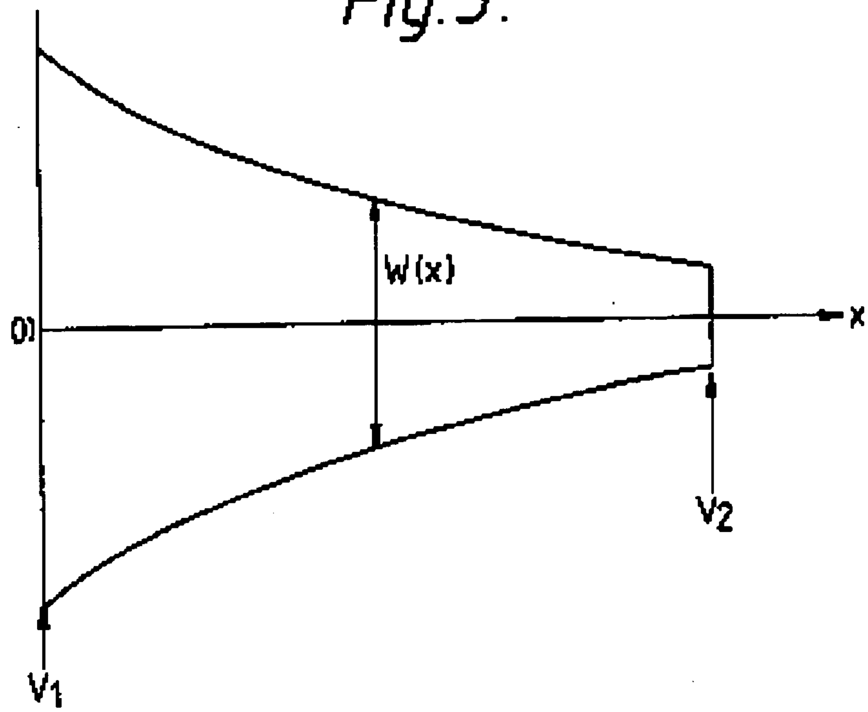


Fig. 4.

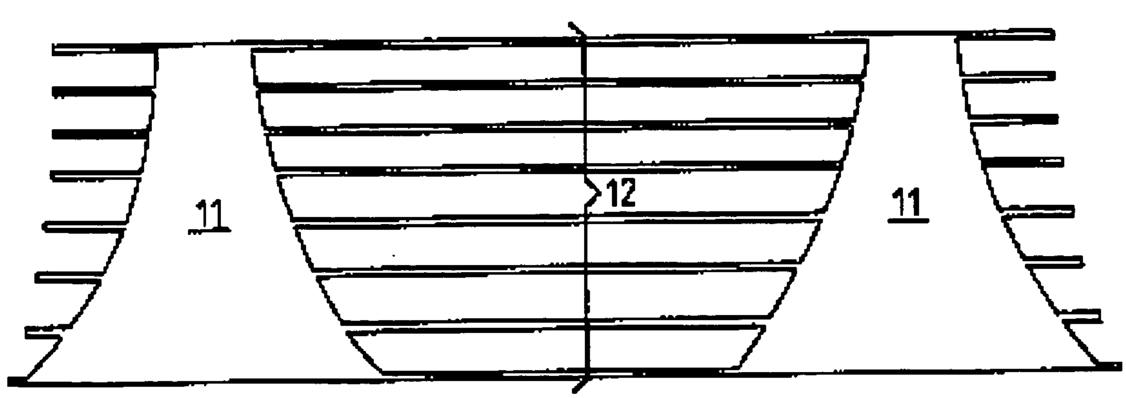
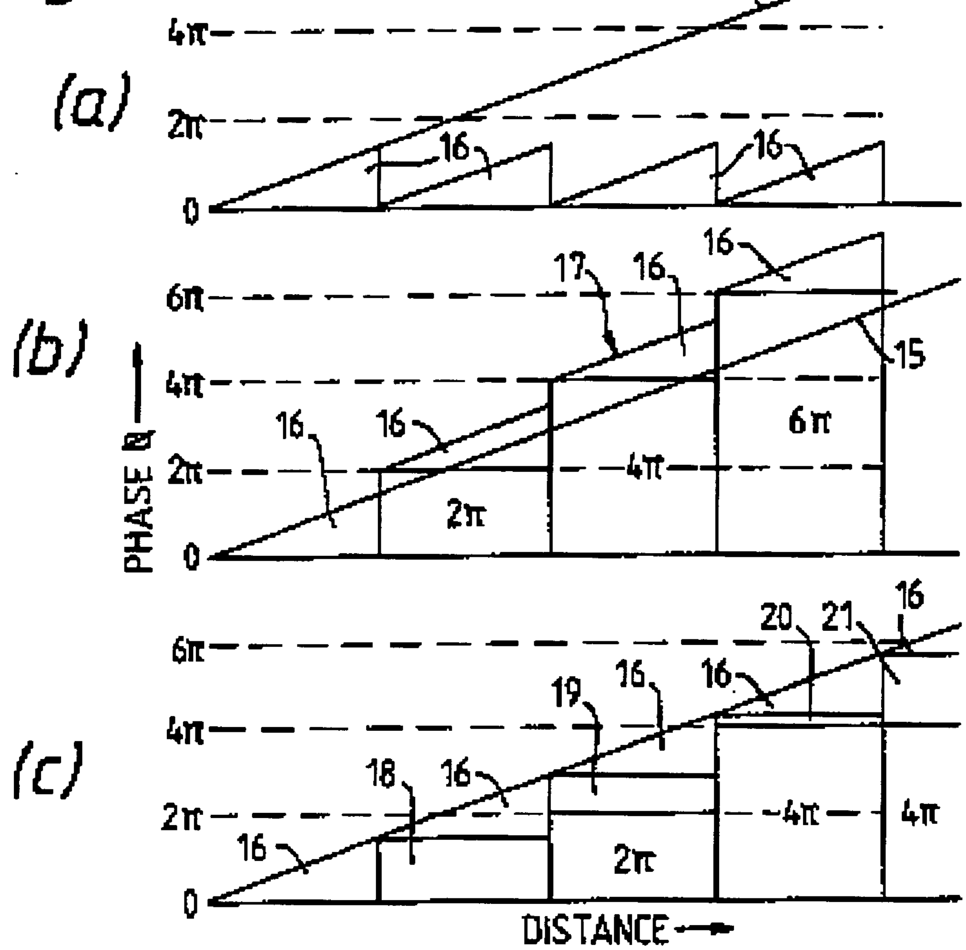


Fig.5.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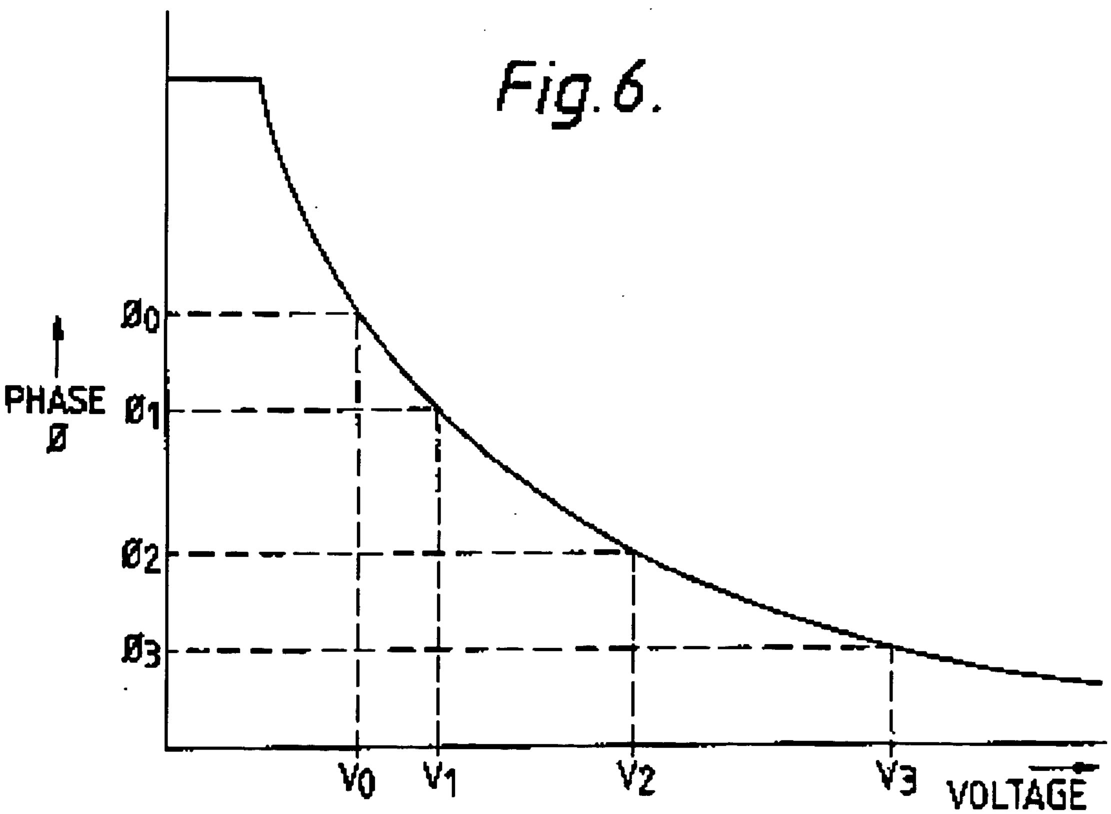
PHASE Ø
DISTANCE

Fig.6.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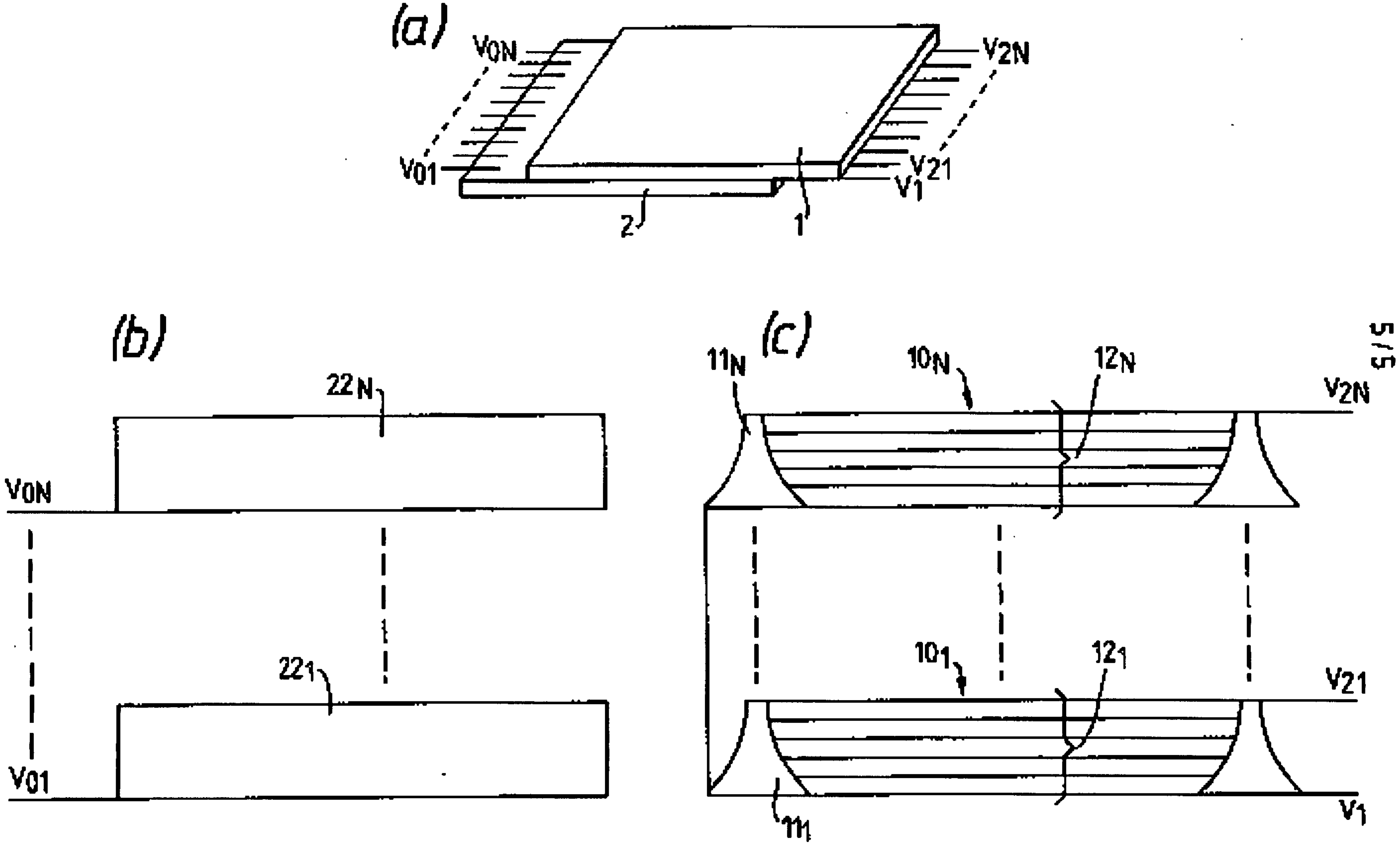
V1
V2
V3
VOLTAGE

Fig. 7.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